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Table 2-8 Elevated temperature properties of glass fiber/nylon 6/6 RPs

Property	Short Fiber		Long Fiber	
	30%	50%	30%	50%
	At 300°F			
Tensile strength (10^3 psi)	12.8	13.8	14.3	19.2
Elongation (%)	9.3	7.8	5.3	5.6
Flexural strength (10^3 psi)	13.8	14.3	17.4	23.7
Flexural modulus (10^5 psi)	4.64	5.27	5.50	8.90
	At 400°F			
Tensile strength (10^3 psi)	6.3	7.3	7.8	8.3
Elongation (%)	8.6	9.5	6.2	6.8
Flexural strength (10^3 psi)	6.9	7.4	8.9	10.0
Flexural modulus (10^5 psi)	3.96	4.80	5.19	7.51

Data on long-fiber glass-reinforced grades are for Verton compounds.
* To convert psi to pascals (Pa), multiply by 6.895×10^3.

surface area for dissipating heat through fins and the like, and other alterations.

As usual with plastics and other materials, sharp comers or abrupt changes in their cross-sectional geometry or wall thickness should be avoided because they can result in weakened, high-stress areas. The areas of high loading where fatigue requirements are high need more generous radii, combined with optimal material distribution. Radii of ten to twenty times are suggested for extruded parts, and one quarter to one half the wall thickness may be necessary for moldings to distribute stress more uniformly over large areas. In evaluating plastics for a particular cyclic loading condition, the type of material and the fabrication variables are quite important. Remember that the many plastics perform differently, whether they are TPs, TSs, unreinforced and reinforced plastics.

The basic rules to providing fatigue endurance can be summarized. Fiber reinforcement provides significant improvements in fatigue with carbon fibers and graphite and aramid fibers being higher than glass fibers (Fig. 2-45). The effects of moisture in the service environment should also be considered, whenever hygroscopic plastics such as nylon, PCs, and others are to be used. For service involving a large number of fatigue cycles in TPs, crystalline-types offer the potential of more predictable results than those based on amorphous types, because the crystalline ones usually have definite fatigue endurance. Also, for optimum fatigue life in service involving both high-stress and fatigue loading, the reinforced high-temperature performance plastics like PEEK, PES, and PI are recommended (Table 2-8).

High Speed Property

For the most part, many of the behavioral characteristics discussed are valid for a wide range of loading rates. There may be significant shifts in behavior, however, at load or strain durations that are much shorter than those discussed, usually take about a second or less to perform (Figs. 2-47 and 2-48). This section deals with loading rates significantly faster than those covered so far, namely rapid and impact loading.

An example of the type, significance, and character of the data obtainable under rapid loads is shown in Fig. 2-49. The data shown describe behavior over a spectrum of elongation rates up to several orders of magnitude higher than those obtained in standard tests. These data illustrate trends for the specific materials examined. (a) Tensile strength usually increases with higher strain rate, for all plastics. (b) The elongation at break decreases with the strain rate. (c) Energy to failure, as determined from the area under the stress-deformation plot, generally

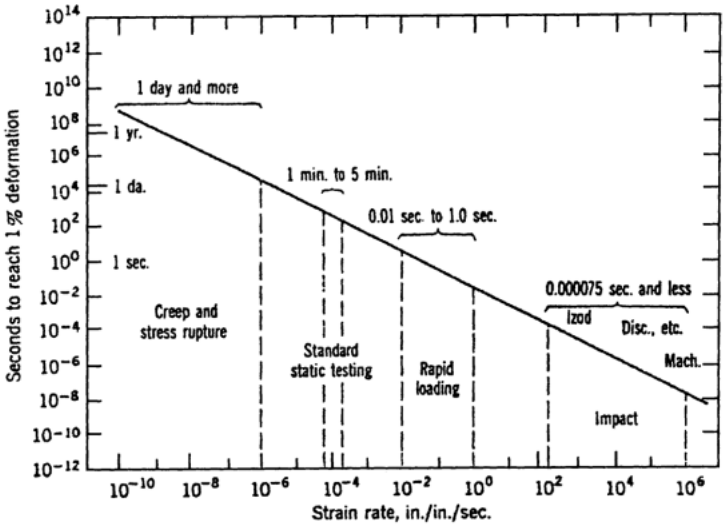

Fig. 2-47 Relation of rapid loading strain rates to those developed in other methods of testing.

decreases or remains the same with an increasing test rate. Moreover, different plastics show a markedly different rate of decay of failure energy with increased test speed.

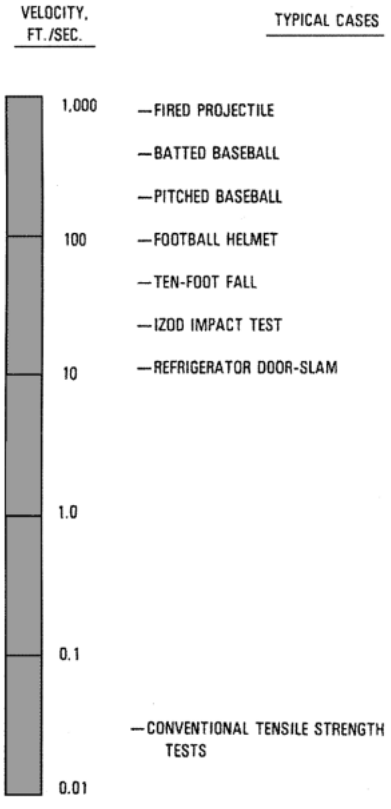

Fig. 2-48 Typical velocities that refer to rapid loading.

Designers with a background in using other materials will recognize both the similarities and the differences in the behavior of the plastics discussed. As an example, impact resistance has been a continuing issue with engineering materials, particularly certain metals with similarities to many of the phenomena observed in plastics.

The concept of a ductile-to-brittle transition temperature in plastics is likewise well known in metals, notched metal products being more prone to brittle failure than unnotched specimens. Of course there are major differences, such as the short time moduli of many plastics compared with those in steel, that may be 30×10^6 psi (207×10^6 kPa). Although the ductile metals often undergo local necking during a tensile test, followed by failure in the neck, many ductile plastics exhibit the phenomenon called a propagating neck. These different engineering characteristics also have important effects on certain aspects of impact resistance.

There are a number of basic forms of energy loads or impingement on products to which plastics react in a manner different from other materials. These dynamic stresses include loading due to impact, impulse, puncture, frictional, hydrostatic, and erosion. They have a difference in response and degree of response to other forms of stress. Analyzing these differences provides

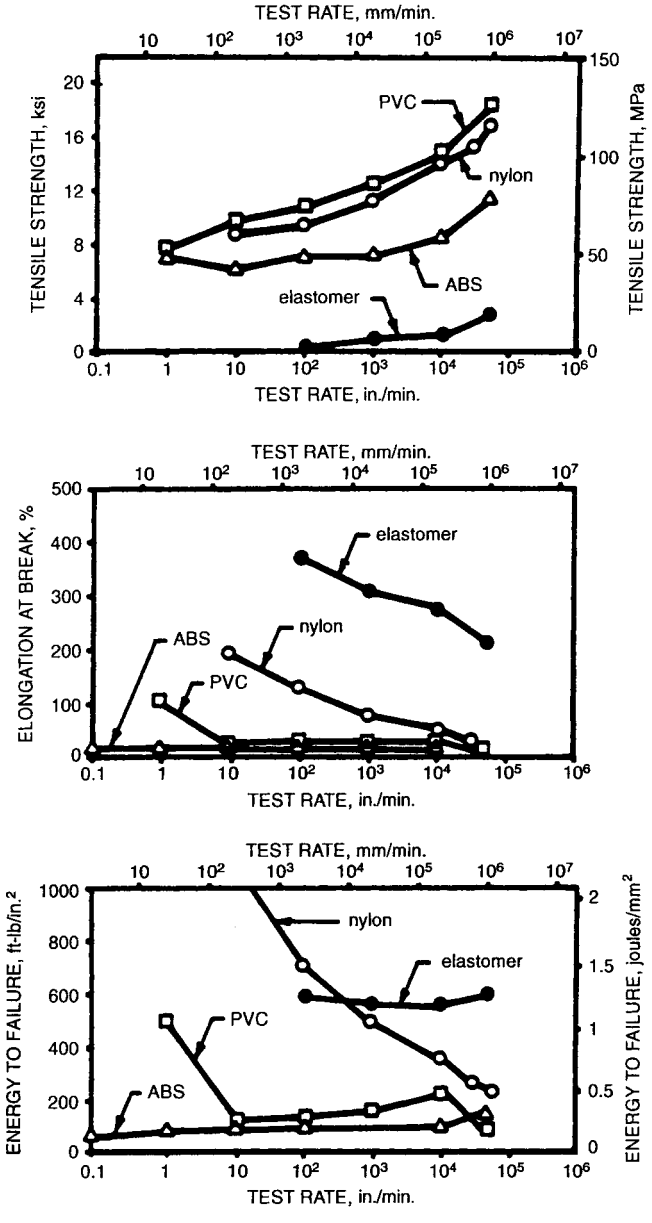

Fig. 2-49 Examples of rapid loading or high speed tests.

the designer with information applicable to product performances.

Impact loading

Whenever a product is loaded rapidly, it can be said to be subjected to impact loading. Any product that is moving has kinetic energy. When this motion is somehow stopped because of a collision, its energy must be dissipated. The ability of a plastic product to absorb energy is determined by such factors as its shape, size, thickness, type of material, method of processing, and environmental conditions of temperature, moisture, and so on. Although the impact strengths of plastics are widely reported, these properties have no particular design value. However, they are important, because they can be used to

provide an initial comparison of the relative responses of materials. Impact strength can pick up a discriminatory response to notch sensitivity. A better value via impact tensile values, is unfortunately not generally reported.

With limitations, the impact value of a material can broadly separate those that can withstand shock loading from those that fare poorly in this response. Of great importance is that they can be compared to the impact performance on the fabricated products. The results provide guidelines that will be more meaningful and empirical to the designer. To eliminate broad generalizations, the target is to conduct impact tests on the final product or, if possible, at least on its components. In conducting impact tests on products the usual problem that has to be resolved as well as possible is how it should be conducted. The real test is after the product has been in service and field reports are returned for evaluation. Regardless, the usual impact tests conducted on test samples can be useful if they are properly coordinated with product requirements.

Design feature The overall impact resistance of a structure is defined as its ability to absorb and dissipate the energy delivered to it during relatively high speed collisions with other objects without sustaining damage that would jeopardize its intended function. Several design features affect impact resistance. For example, rigidizing elements such as ribs may decrease a part's impact resistance, while less-rigid sections may absorb more impact energy without damage by deflecting elastically.

Likewise, dead sharp corners or notches subjected to tensile loads during impact may decrease the impact resistance of a product by acting as stress concentrators, whereas generous radii in these areas may distribute the tensile load and enhance the impact resistance. This point is particularly important for products comprised of materials whose intrinsic impact resistance is a strong function of a notch radius. Such notch sensitive materials are characterized by an impact resistance that decreases drastically with notch radius. Wall thickness may also affect impact resistance. Some materials have a critical thickness above that the intrinsic impact resistance decreases dramatically.

Impact loads are a particularly important kind of load for plastics. While many materials such as PE and nylon have good impact strength, other plastics such as crystal PS and some grades of PVC have low impact strength. Many of the tests for impact strength have been based on tests for steel and other metals and the applicability of such tests to plastics has always been questionable. For example PVC which rates low in notched Izod impact tests performs well in normal applications that involve impact loading. However, some grades of rubber-modified high impact styrenes that show up well in the Izod test break on impact under field test conditions. These results have led to continual reexamination of the tests used to determine the toughness of plastics.

Methods employed to determine the impact resistance of plastics include: pendulum methods (Izod, Charpy, tensile impact, falling dart, Gardner, Dynatup, etc.) and instrumented techniques. In the case of the Izod test, what is measured is the energy required to break a test specimen transversely struck (the test can be done either with the specimen notched or unnotched). The tensile impact test has a bar loaded in tension and the striking force tends to elongate the bar (Chapter 5, **Impact Strength**).

There are plastics that tend to be very notch sensitive on impact. This is apparent from the molecular structure of the materials that consist of random arrangements of plastic chains. If the material exists in the glassy state at room temperature the notch effect is to cut the chains locally and increase the stress on the adjacent molecular chains which will scission and propagate the effect through the material. At the high loading rate encountered in impact loading the only form of molecular response is the chain bending (spring) reaction which is limited in extent and generally low in magnitude compared to the viscoelastic response which responds at longer loading times.

There are several ways in which the impact properties of plastics can be improved if the material selected does not have sufficient impact strength. One method is by altering the composition of the material so that it is no longer a glassy plastic at the operating temperature of the product (Chapter 6). In the case of PVC this is done by the addition of an impact modifier which can be a compatible plastic such as an acrylic or a nitrile rubber. The addition of such a material lowers the glass transition temperature and the material becomes a rubbery viscoelastic plastic with much improved impact properties. This is one of the methods in which PVC materials are made to exhibit superior impact properties.

Another way in which to improve impact properties is by orienting the material. Nylon has a fair impact strength but oriented nylon has a very high transverse impact strength. The intrinsic impact strength of the nylon comes from the polar structure of the material and the fact that the polymer is crystalline. The substantial increase in impact strength as a result of the orientation results from the molecular chains being aligned. This makes them very difficult to break and, in addition, the alignment improves the polar interaction between the chains so that even when there is a chain break the adjacent chains hold the broken chain and resist parting of the structure. The crystalline nature of the nylon material also means that there is a larger stress capability at rapid loading since the crystalline areas react much more elastically than the amorphous glassy materials.

Other methods in which impact strength can be substantially improved is by the use of fibrous fillers. These materials act as a stress transfer agent around the region that is highly stressed by the impact load. Since most of the fibrous fillers such as glass and asbestos have high elastic moduli, they are capable of responding elastically at the high loading rates encountered in impact loading (39).

One general method of improving the performance of plastic products in impact loading is to prevent, by design and handling, the formation of notched areas which act as stress risers. Especially under impact conditions the possibility of localized stress intensification can lead to product failure. In almost every case the notched strength is substantially less than the unnotched strength.

It is important to recognize that impact strength is sensitive to temperature conditions. The impact strength of plastics is reduced drastically at low temperatures with the exception of fibrous filled materials that improve in impact strength at low temperature. The reduction in impact strength is especially severe if the material undergoes a glass transition where the reduction in impact strength is usually an order of magnitude.

Impulse Loading

A related form of stress to impact is impulse loading that differs in two ways from impact loading. Impact loading implies striking the object and consequently there is a severe surface stress condition present before the stress is transferred to the bulk of the material. In addition, in impact loading the load is applied instantly, limited in straining rate only by the elastic constants of the material being struck. A significant portion of the energy of impact is converted to heat at the point of impact and complicates any analytically exact treatment of the mechanics of impact.

In the case of impulse loading the load is applied at very high rates of speed limited by the member applying the load. However, the loading is not generally localized and the heat effects are similar to conventional dynamic loading in that the hysteresis characteristics of the material determines the extent of heating and the effects can be analyzed with reasonable accuracy. For example, the load of two billiard balls striking is definitely an impact condition. The load applied to a brake shoe when the brake is applied or the load applied to a fishing line when a strike is made is an impulse load. The time constants are short but not as short as the impact load and the entire structural element is subjected to the stress.

Plastics generally behave in a much different manner under impulse loading than they do under loading at normal straining rates. Some of the same conditions occur as under impact loading where the primary response to load is an elastic one because there is not sufficient time for the viscoelastic elements to operate. The primary structural response in the polymer is by chain bending and by stressing of the crystalline areas of crystalline polymers. The response to loading is almost completely elastic for most materials, particularly when the time of loading is of the order of milliseconds.

Since the entire load is applied to the elastic elements in the structure and the long-range strain adaptation is precluded, the material will exhibit a high elastic modulus and much lower strain to rupture. It is difficult to generalize as to whether the material is stronger under impulse loading than under normal loading. For example, PMMA and rigid PVC materials that appear to be brittle under normal loading conditions, exhibit high strength under impulse loading conditions. Rubbery materials such as thermoplastic urethane elastomers and some other elastomers behave like brittle materials under impulse loading. This is an apparently unexpected result that upon analysis is obvious because the elastomeric rubbery response is a long time constant response and the rigid connecting polymer segments which are brittle are the ones that respond at high loading rates.

The comments regarding improvements made with respect to impact loading for structures apply equally well to impulse loading conditions. Fibrous fillers improve impulse loading strength. Oriented materials withstand impulse loading much better than unoriented materials. As an example fibrous forms of materials are used in rope because they take impulse loading well. Crystalline polymers generally perform well under impulse loading, especially polar materials with high interchain coupling.

Using plastics under impulse loading conditions requires a careful design approach. Test data taken with high-speed testing machines are essential before using a plastic for these applications since it is difficult to predict the response of the material from the available data. High-speed testing machine are used to determine the response of materials at millisecond loading rates. In the absence of such test data, the only first sorting evaluation that can be done is from the results of the tensile impact test. The test should be done with a series of loads below break load, through the break load, and then estimating the energy of impact under the non-break conditions as well as the tensile impact break energy. As indicated above, apparently brittle materials perform well and rubbery materials that would seem to be a natural for impulse loading behave in a brittle manner.

Puncture Loading

Resistance to puncture is another type of loading. It is of particular interest in applications involving sheet and film as well as thin-walled tubing or molding and other membrane type loaded structures. The surface skins of sandwich panels are another area where it is important. A localized force is applied by a relatively sharp object perpendicular to the plane of the sheet of material being stressed. If the material is thick compared to the area of application of the stress, it is effectively a localized compression stress with some shear effects as the material is deformed below the surface of the sheet.

In the case of a thin sheet or film the stresses cause the material to be displaced completely away from the plane of the sheet and the restraint is by tensile stress in the sheet and by hoop stress around the puncturing member. Most cases fall somewhere between these extremes, but the most important conditions in practice involve the second condition to a larger degree than the first condition.

To analyze the second condition take the material at the point where the puncturing object has almost pierced the membrane but has not broken through. At this point one can see the nature of the forces which are

resisting the puncture and qualitatively relate them to the primary physical characteristics of the material so that we can indicate which materials are suitable for resistance to this type of stress and how to improve the resistance to puncture.

There are three principal stresses that result from the puncture forces through relatively thin material. They are a compressive stress under the point of the puncturing member, a tensile stress caused by the stretching of the material under the penetrating force, and a hoop stress caused by the material being displaced around the penetrating member. Part of the hoop stress is compressive adjacent to the point which changes to tensile stress to contain the displacing forces. It is evident that anisotropic materials will have a more complicated force pattern and, in fact, uniaxially oriented materials will split rather than puncture under this type of loading. To improve the puncture resistance materials are needed with high tensile strength. This is evident as required to have both the stretching load and the hoop stress. In addition, the material should have a high compression modulus to resist the point penetration into the material. Resistance to notch loading is also important.

Based on this analysis it is evident that materials which are biaxially oriented will have good puncture resistance. Highly polar polymers would be resistant to puncture failure because of their tendency to increase in strength when stretched. The addition of randomly dispersed fibrous filler will also add resistance to puncture loads. From some examples such as oriented polyethylene glycol terephthalate (Mylar), vulcanized fiber, and oriented nylon, it is evident that these materials meet one or more of the conditions reviewed. Products and plastics that meet with puncture loading conditions in applications can be reinforced against this type of stress by use of a surface layer of plastic with good puncture resistance. Resistance of the surface layer to puncture will protect the product from puncture loads. An example of this type of application is the addition of an oriented PS layer to foam cups to improve their performance.

Frictional Loading

The frictional properties of plastics are of particular importance to applications in machine products and in sliding applications such as belting and structural units such as sliding doors. The range of friction properties are rather extensive. The relationship between the normal force and the friction force is used to define the coefficient of static friction.

Friction coefficients will vary for a particular material from the value just as motion starts to the value it attains in motion. The coefficient depends on the surface of the material, whether rough or smooth, as well as the composition of the material. Frequently the surface of a particular plastics will exhibit significantly different friction characteristics from that of a cut surface of the same smoothness. These variations and others that are reviewed make it necessary to do careful testing for an application which relies on the friction characteristics of plastics. Once the friction characteristics are defined, however, they are stable for a particular material fabricated in a stated manner.

The molecular level characteristics that create friction forces are the intermolecular attraction forces of adhesion (2). If the two materials that make up the sliding surfaces in contact have a high degree of attraction for each other, the coefficient of friction is generally high. This effect is modified by surface conditions and the mechanical properties of the materials. If the material is rough there is a mechanical locking interaction that adds to the friction effect. Sliding under these conditions actually breaks off material and the shear strength of the material is an important factor in the friction properties. If the surface is not rough, but smoothly polished, the governing factor induced by the surface conditions is the amount of area in contact between the surfaces. In a condition of large area contact and good adhesion, the coefficient of friction is high. In the case of smoothly polished surfaces and adhesion forces the coefficient is very high since there is intimate surface contact.

Several other factors affect the frictional forces. If one or both of the contacting surfaces have a relatively low compression modulus it is possible to make intimate contact between the surfaces which will lead to high friction forces in the case of plastics having good adhesion. It can add to the friction forces in another way. The displacement of material in front of the moving object adds a mechanical element to the friction forces.

All sliding friction forces are dramatically affected by surface contamination. If the surface is covered with a material that prevents the adhesive forces from acting, the coefficient is reduced. If the material is a liquid which has low shear viscosity the condition exists of lubricated sliding where the characteristics of the liquid control the friction rather than the surface friction characteristics of the materials. It is possible by the addition of surface materials that have high adhesion to increase the coefficient of friction.

The use of plastics for gears and bearings is the area in which friction characteristics have been examined most carefully. As an example highly polar polymers such as nylons and the TP polyesters have, as a result of the surface forces on the material, relatively low adhesion for themselves and such sliding surfaces as steel. Laminated plastics also make excellent bearings. The physical properties of these materials make them a good choice for both bearing and gear materials. The typical coefficient of friction for such materials is 0.1 to 0.2.

In the injection molded condition the skin formed when the plastic cools against the mold tends to be harder and slicker than a cut surface so that the molded product exhibit lower sliding friction and are excellent for this type of application. Good design for this type of application is to make the surfaces as smooth as possible without making them glass smooth which tends to increase the intimacy of contact and to increase the friction above that of a fine surface. The problems in this type of application related to friction are heat effects due to the rubbing surfaces. For successful design the heat generated by the friction must be dissipated as fast as it is generated to avoid overheating and failure.

Obviously the addition of appropriate lubricants will lower the friction and help to remove the heat. There are several other ways in which the friction can be reduced. One is by the incorporation of fillers. The fillers can be used to increase the thermal conductivity of the material such as glass and metal fibers. The filter can be a material like TFE plastic that has a much lower coefficient of friction and the surface exposed material will reduce the friction. Another approach that is used is the incorporation of slightly incompatible materials such as silicone oil into the molding material. After molding the material migrates to the surface of the product and acts as a renewable source of lubricant for the product. In the case of bearings it is carried still further by making the bearing material porous and filling it with a lubricating material in a manner similar to sintered metal bearings, graphite and molybdenum sulfide are also incorporated as solid lubricants.

A different type of low friction or low drag application is encountered with sliding doors or conveyor belts sliding on support surfaces. In applications like this the normal forces are generally quite small and the friction load problems are of the sticking variety. Some plastics exhibit excellent track surfaces for this type of application. TFEs have the lowest coefficient of any solid material and represent one of the most slippery surfaces known. The major problem with TFE is that its abrasion resistance is low so that most of the applications utilize filled compositions with ceramic filler materials to improve the abrasion resistance.

There is a whole field of applications for TFE in reducing friction using solid materials as well as films and coatings. Another material with excellent properties for surface sliding is ultra high molecular weight polyethylene (UHMWPE). Polyethylene and the polyolefins in general have low surface friction, especially against metallic surfaces. The UHMWPE has an added advantage in that it has much better abrasion resistance and is preferred for conveyor applications and applications involving materials sliding over the product. In the textile industry loom products also use this material extensively because it

can handle the effects of the thread and fiber passing over the surface with low friction and relatively low wear.

The specific friction characteristics of plastics at the high friction end are also an area of significant applications. Some plastics, notably polyurethanes and some plasticized vinyl compositions, have very high friction coefficients. These materials make excellent traction surfaces for products ranging from power belts to drive rollers where the plastics either drives, or is driven, by another member. Conveyor belts made of oriented nylon and woven fabrics are coated with polyurethane elastomer compounds to supply both the driving traction and to move the objects being conveyed up fairly steep inclines because of the high friction generated. Drive rollers for moving paper through printing presses and business machines are frequently covered with either urethane or vinyl to act as the driver members with minimum slippage. The materials are also used as the torque surfaces in clutches and brakes.

In all of the friction applications suggested as well as in many others, there are two areas where the design effort is introduced. The first is in material selection and modification to provide either high or low friction as required by the application. The other is in determining the required geometry to supply the frictional force level needed by controlling contact area and surface quality to provide friction level. A controlling factor limiting any particular friction force application is heat dissipation. This is true if the application of the friction loads is either a continuous process or a repetitive process with a high duty cycle. The use of cooling structures either incorporated into the products or by the use of external cooling devices such as coolants or air flow should be a design consideration.

Hydrostatic Loading

This is another behavior to be considered in this type of loading. The surface properties of the material are quite significant. If the water does not wet the surface, the tendency will be to have the droplets that do not impact close to the perpendicular direction bounce off the surface with considerably less energy transfer to the surface. Non-wetting coatings reduce the effect of wind and rain erosion.

Impact of air-carried solid particulate matter is more closely analogous to straight impact loading since the particles do not become disrupted by the impact. The main characteristic required of the material, in addition to not becoming brittle under high rate loading, is resistance to notch fracture. The ability to absorb energy by hysteresis effects is also important as is the case with the water. In many cases the best type of surface is an elastomer with good damping properties and good surface abrasion resistance. An example is polyurethane coatings and products that are excellent for both water and particulate matter that is air-driven. Besides such applications as vehicles, these materials are used in the interior of sand and shot blast cabinets where they are constantly exposed to this type of stress. These materials are fabricated into liners in hoses for carrying pneumatically conveyed materials such as sand blasting hoses and for conveyor hose for a wide variety of materials such as sand, grain, and plastics pellets.

In general when the surface impact loading by fluid-borne particulate matter, liquid or solid, or cavitation loading is encountered, the method of minimizing the effects of erosion produced are by material selection and modification. The plastics used should be ductile at impulse loading rates and capable of absorbing the impulse energy and dissipating it as heat by hysteresis effects. The surface characteristics of the materials in terms of wettability by the fluid and frictional interaction with the solids also play a role. In this type of application the general data available for materials should be supplemented by that obtained under simulated use conditions since the properties needed to perform are not readily predictable from the usually available data.

Another loading condition in underwater applications is the application of external hydrostatic stress to plastic structures (also steel, etc.). Internal pressure applications such as those encountered in pipe and

tubing or in pressure vessels such as aerosol containers are easily treated using tensile stress and creep properties of the plastic with the appropriate relationships for hoop and membrane stresses (108). The application of external pressure, especially high static pressure, has a rather unique effect on plastics. The stress analysis for thick walled spherical and tubular structures under external pressure are available.

The interesting aspect that plastics have in this situation is that the high compressive stresses increase the resistance of plastic materials to failure. Glassy plastics under conditions of very high hydrostatic stress behave in some ways like a compressible fluid. The density of the material increases and the compressive strength is increased. In addition, the material undergoes sufficient internal flow to distribute the stresses uniformly throughout the product. As a consequence, the plastic products produced from such materials as PMMA and PC make excellent view windows for undersea vehicles that operate at extreme depths where the external pressures are 1000 psi (7MPa) and more.

Erosion Loading

This subject is emphasizing a specialty high speed loading that is part of the previous section on hydrostatic loading. It is the effect of erosion forces such as wind driven sand or water, underwater flows of solids past plastic surfaces and even the effects of high velocity flows causing cavitation effects on material surfaces. One major area for the utilization of plastics is on the outside of moving objects that range from the front of automobiles to boats, aircraft, missiles, and submarine craft. In each case the impact effects of the velocity driven particulate matter can cause surface damage to plastics. Stationary objects such as radomes and buildings exposed to the weather in regions with high and frequent winds are also exposed to this type of effect.

A type of wind erosion analysis that has been extensively studied is the effect of water drop erosion on rapidly moving missile parts. Aircraft radomes have also been extensively studied for the effects of wind-driven water and solids. The erosion effects are very dramatic and the surfaces are usually protected with elastomeric materials that have good resistance to this type of stress.

To determine the type of physical properties materials used in this environment should have, it is necessary to examine the mechanics of the impact of the particulate matter on the surfaces. The high kinetic energy of the droplet is dissipated by shattering the drop, by indenting the surface, and by frictional heating effects. The loading rate is high as in impact and impulse loading, but it is neither as localized as the impact load nor as generalized as the impulse load, Material that can dissipate the locally high stresses through the bulk of the material will respond well under this type of load. The plastic should not exhibit brittle behavior at high loading rates.

In addition, it should exhibit a fairly high hysteresis level that would have the effect of dissipating the sharp mechanical impulse loads as heat. The material will develop heat due to the stress under cyclical load. Materials used are the elastomeric plastics used in the products or as a coating on products.

Cavitation erosion With increasing ship speeds, the development of high-speed hydraulic equipment, and the variety of modem fluid-flow applications to which metal materials are being subjected, the problem of cavitation erosion becomes ever more important. Erosion may occur in either internal-flow systems, such as piping, pumps, and turbines, or in external ones like ships' propellers (36).

Osborne Reynolds identified the phenomenon of cavitation as early as 1873. By the turn of the century it had been called by its present name by R. E. Froude, the director of the British Admiralty Ship Model Testing Laboratories.

Cavitation occurs in a rapidly moving fluid when there is a decrease in pressure in the fluid below its vapor pressure and the presence of such nucleating sources as minute foreign particles or definite gas bubbles. As a result, vapor bubble forms that continues to grow until it reaches a region of pressure

higher than its own vapor pressure, when it collapses. When these bubbles collapse near a boundary, the high-intensity shock waves that are produced radiate to the boundary, resulting in mechanical damage to the material. The force of the shock wave or of the impinging may still be sufficient to cause a plastic flow or fatigue failure in a material after a number of cycles, depending on the properties of the material, the existing hydrodynamic conditions, and the foil-design parameters.

The behavior of materials, particularly steel, in cavitating fluids results in an erosion mechanism, including mechanical erosion and electrochemical corrosion. The straightforward way to fight cavitation is to use hardened materials, chromium, chrome-nickel compounds, or elastomeric plastics. Other cures are to reduce the vapor pressure with additives, reduce the turbulence, change the liquid's temperature, or add air to act as a cushion for the collapsing bubbles.

Rain erosion One that walks through a gentle spring rain seldom considers that raindrops can be small destructive "bullets" when they strike high-speed aircraft. These bulletlike raindrops can erode paint coatings, plastic products, and even steel, magnesium, or aluminum leading edges to such an extent that the surfaces may appear to have been sandblasted. Even the structural integrity of the aircraft may be affected after several hours of flight through rain. This problem is of special interest to aircraft engaged in all weather flying.

It affects commercial aircraft, missiles, high-speed vehicles on the ground, spacecraft before and after a flight when rain is encountered, and even buildings or structures that undergo high-speed rainstorms. The critical situations exist in flight vehicles, since flight performance can be affected to the extent that a vehicle can be destroyed. Research and development concerning rain erosion on aircraft has been extensive since the 1940s.

Erosion by rain of the exterior of so called (at that time) high-speed aircraft during flight was observed during World War 11 on all-weather fighter airplanes capable then of only flying at 400 mph. The aluminum edges of wings and particularly of the glass-fiber-reinforced TP polyester-nose radomes (particularly the long Eagle Wing on B-29s flying over the Pacific) were particularly susceptible to this form of degradation. The problem continues to exist as can be seen on the front of commercial and military airplanes with their neoprene protective coated RP radomes; the paint coating over the rain erosion elastomeric plastic erodes and then is repainted prior to the rain erosion elastomeric coating is affected.

Actual flight tests to determine the severity of this phenomenon of rain erosion carried out in 1943 established that aluminum and RP leading edges of airfoil shapes exhibited serious erosion after exposure to rainfall of only moderate intensity. Inasmuch as this problem originally arose with military aircraft, the U.S. Air Force initiated research studies at the Wright-Patterson Development Center's Materials Laboratory in Dayton, Ohio. Based on the results of a young girl physicist (worked for DVR), it resulted in applying an elastomeric neoprene coating adhesively bonded to RP radomes. The usual 5-mil coating of elastomeric material used literally bounces off raindrops, even from a supersonic airplane traveling through rain. There is a slight loss of radar transmission of about 1% per mil of the plastic thickness, but this is better than losing 100% when the radome is destroyed.

Thermal Expansion and Contraction

Unconstrained specimens of almost all materials respond to temperature increases by expanding and to temperature decreases by contracting. The coefficient of linear thermal expansion (CLTE) of a material is determined by varying the temperature of a representative test specimen. Measurement is made of its length as a function of temperature over the desired range, computing the total change in specimen length over that range, and then dividing that change in length by both the specimen length at the

reference temperature and the total temperature excursion. In determining the coefficient of linear thermal expansion of plastics per ASTM D696, the temperature range is −30°C to +30°C (−22 to +86°F); and the reference temperature is 23°C (73°F).

There are plastics that have equal or less than those of other materials of construction (metals, glass, or wood). In fact with certain additives such as graphite powder contraction can occur rather than the expected expansion with the application of heat. However many plastics typically have coefficients that are considerably higher than those of other materials of construction such as metals. This difference may amount to a factor of 10 to 30. Also available are plastics, particularly TS-RPs, with practically no change.

Obviously, the designer must take thermal expansion and contraction into account if critical dimensions and clearances are to be maintained during use where material is in a restricted design. Less obvious is the fact that products may develop high stresses when they are constrained from freely expanding or contracting in response to temperature changes. These temperature-induced stresses can cause material failure.

Plastic products are often constrained from freely expanding or contracting by rigidly attaching them to another structure made of a material (plastic, metal, etc.) with a lower coefficient of linear thermal expansion. When such composite structures are heated, the plastic component is placed in a state of compression and may buckle, etc. When such composite structures are cooled, the plastic component is placed in a state of tension, which may cause the material to yield or crack. The precise level of stress in the plastic depends on the relative compliance of the component to which it is attached, and on assembly stress.

To minimize the stresses induced by differential thermal expansion/contraction one must: (1) employ fastening techniques that allow relative movement between the component parts of the composite structure, (2) minimize the difference in coefficient of linear thermal expansion between the materials comprising the structure; and/or (3) minimize the temperature differences the structure will experience during use or shipment. Examples of proper fastening methods include the use of screws, bolts, spring clips, etc. with oversize holes, slots, or compliant bushings.

Hysteresis Effect

The hysteresis heating failure occurs more commonly in plastic members subject to dynamic loading. It would be well to point out what comprises dynamic loading and what types of stresses are encountered. One example commonly encountered is a plastic gear. In the course of operation the gear teeth are periodically, once per revolution, subjected to a bending load that transmits the power from one gear to another. Another example is a link that is used to move a paper sheet in a copier or in an accounting machine from one operation to the next. The load may be simple tensile or compressive stresses, but more commonly it is a bending load.

There are some less obvious but quite important dynamic stress situations that illustrate the importance of dynamic loading. A belt that is used to drive a pulley is subject to repeated bending and tensile stresses during operation. A tire on a vehicle is subjected to a complicated combination of bending, bearing, and compressive stresses during the movement of the vehicle that it supports. The keys on a computer or printer are subjected to repeated impulse loading during use even though the action is not strictly cyclical in nature. Add to this the effects of vibration induced by vehicle motion or machine action that is an induced cyclical stress in products that are attached to the vibration-inducing object and it becomes apparent that cyclical loading is a widely encountered type of loading. In many instances the dynamic stress exists in conjunction with static stresses and with other longer-term periodic loads.

An example will be given to show how dynamic loading can lead to product failure by hysteresis heating. When this condition exists the failure will be catastrophic rather than

gradual. This is not generally true of creep failure or of normal fatigue failure. The example is a link that is loaded in tension and is the connecting link that drives a flywheel type of unit by means of a linear actuating force. The primary load on the product is alternate tension and compression loading. The compression loading is low since it represents the flywheel driving the link back against friction forces. The tensile force is the driving force and it varies from zero to a maximum that is determined by the torque load on the flywheel member.

The relationship of force to time is determined using engineering equations (Appendix A: **PLASTICS DESIGN TOOLBOX**). Result is the force function per revolution and this divided by the time of a revolution will give the force as a function of time. Increasing temperature increases heat transfer from the product to the surroundings and if the rate of heat transfer equals the rate of heat generation at a temperature below the softening temperature of the material, the process will stabilize and the product will not fail. It is apparent that the major factor in hysteresis failure is not the ability of the product to dissipate the heat generated to its surroundings (190).

The designer can use several approaches to prevent hysteresis failure. The first is material selection. The stiffer the material is, the smaller the strain is for a given stress level and the lower the hysteresis loss per cycle. Some materials are additionally fairly linear in stress-strain characteristics and have smaller hysteresis loops. These would be preferred in dynamic loading applications.

Another approach is to improve the heat transfer conditions from the product. This can be accomplished in several ways. One way is to operate in a coolant medium that would also act as the lubricant for the system. The heat transfer to a liquid is usually much better than to air, and the liquid can be cooled by passing it through a heat exchanger device. A second approach is to improve the heat transfer to air. This can be done by increasing the surface area of the product by means of fins or other surface projections. The larger area will increase the heat flow out of the product substantially. The third approach is the use of air circulating techniques which can be areas added to the stressed unit such as air deflector sections or the use of fan cooling as part of the system. An approach that may fit some applications is the use of metal heat-sink elements buried in the plastic that conducts the heat into other parts of the complete machine to dissipate it to the surroundings.

Basically, anything that can be done to reduce the temperature of the product by removal of heat generated by the cyclical stress will improve the possibilities of surviving the cyclical stress. If the heat transfer capability is limited, then the only alternative is to use stiff materials and low stress levels on the product compared with the strength capability of the material. The heavier products that result will be relatively inefficient in the use of material. In some cases when the load applied is an inertial load (such as an impeller on a pump) it may be that only a trade-off of weight for low stress level can cause failure.

Energy and Motion Control

There are plastics such as TP elastomers that are frequently subjected to dynamic loads where heat energy and motion control systems are required. One of the serious dynamic loading problems frequently encountered in machines and vehicles is vibration-induced deflection (Chapter 4, **DYNAMIC LOAD ISOLATOR**).

Such effects can be highly destructive, particularly if a product resonates at one of the driving vibration frequencies. One of the best ways to reduce and in many cases, eliminate vibration problems is by the use of these viscoelastic plastics. Some materials such as silicone elastomers, flexible vinyl compounds of specific formulations, polyurethane plastics, and a number of others have very large hysteresis effects. By designing them into the structure it is possible to have the viscoelastic material absorb enough of the vibration inducing energy and convert it to heat so that the structure is highly damped and will not vibrate. In each case the viscoelastic

material is arranged in such a way that movement or flexing of the product results in large deflections of the viscoelastic materials so that a large hysteresis curve is generated with a large amount of energy dissipated per cycle.

By calculating the energy to heat it is possible to determine the vibration levels to which the structure can be exposed and still exhibit critical damping. There is one area that must be evaluated. Plastics exhibit a spectrum of response to stress and there are certain straining rates that the material will react to almost elastically. If this characteristic response corresponds to a frequency to which the structure is exposed the damping effect is minimal and the structure may be destroyed. In order to avoid the possibility of this occurring, it is desirable to have a curve of energy absorption vs. frequency for the material that will be used.

Viscoelastic damping The same approach can be used in designing power transmitting units such as belts. In most applications it is desirable that the belts be elastic and stiff enough to minimize heat buildup and to minimize power loss in the belts. In the case of a driver which might be called "noisy" in that there are a lot of erratic pulse driven forces present, such as an impulse operated drive, it is desirable to remove this noise by damping out the impulse and get a smooth power curve.

This is easily done using a viscoelastic belt that will absorb the high rate load pulses. The same approach can be used by making one gear in a gear train or one link in a linear drive mechanism an energy absorber. The viscoelastic damping can be a valuable tool for the designer to cope with impulse loading that is undesirable and potentially destructive to the product.

There is another type of application where the damping effect of plastic structures can be used to advantage. It has a long although not obvious history. The early airplanes used doped fabric as the covering for wings and other aerodynamic surfaces. The dope was cellulose nitrate and later cellulose acetate that is a damping type of plastic. Consequently, surface flutter was a rare occurrence. It became a serious problem when aluminum replaced the fabric because of the high elasticity of the metal surfaces. The aerodynamic forces acting on the thin metal coverings can easily induce flutter and this was a difficult design problem that was corrected for minimizing the effect.

Weathering/Environment

Plastics have been used, and used very successfully, in applications where continuous or intermittent exposure to weather and different environments has been involved. The successes, however, have been the result of thoughtful and discriminating sifting of the weatherability data, rather than blind choice or wishful thinking. Due to their extreme versatility, plastics are used in almost every imaginable type of media. Not only must they resist weather and temperature extremes ranging from cryogenic to above 1,370°C (2,500°F) heat generated in rocket motors, but also extreme conditions of corrosion, irradiation, fluid degradation as typified by liquid rocket propellants, and mechanical energy such as abrasion.

Like other materials with which designer's work, different plastics can be sensitive to the environments. Even ordinary exposure from sunlight or to household cleaning agents can change the properties of certain plastics. Whereas rust, corrosion, and loss of its properties can plague metals, the cracking, crazing, and loss of its properties can affect certain plastics in the presence of different environments.

The age-old problem of predicting what will happen to any material after it is subjected to service also exists with plastics. Different data on plastics are available, but typical of so-called progress, there is never sufficient or adequate useful information to predict the service life of products being designed. It is suggested that rather than assume that a lack of data exists, one should determine what is logically available and apply it most efficiently. A potential example of improper design with plastics concerns toys.